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research division

To: Mr. M.L. Walsh
Manager, Technical Safety Standards
Health & Safety Division Pickering 03P52

A SIMPLE MODEL FOR CALCULATING RESIDENTIAL 60 Hz MAGNETIC FIELDS

D.L. Mader, D.A. Barrow, K.E. Donnelly, R.R. Scheer and M.D. Sherar

ABSTRACT

A model is presented which permits the calculation of 60 Hz magnetic fields throughout a residence from only a few measurements. We assume that residential magnetic fields are produced by sources external to the house and by the residential grounding circuit. The field from external sources is measured with a single probe. The field produced by the grounding circuit is calculated from the current flowing in the circuit and its geometry. The two fields are combined to give a prediction of the total field at any point in the house. A data acquisition system was built to record the magnitude and phase of the grounding current and the field from external sources. Model predictions were compared with measurements of the total magnetic field at a single location in 23 houses and a correlation coefficient of 0.87 was obtained, indicating that the model has good predictive capability. A more detailed study carried out in one house compared measurements with model predictions at locations throughout the house. Again, quite reasonable agreement was found. We also investigated the temporal variability of field readings in this house. Daily magnetic field averages were found to be considerably more stable than hourly averages. Finally, we demonstrate use of the model in creating a profile of the magnetic fields found in a home.

INTRODUCTION

A hypothesis that 60 Hz magnetic fields may have health effects has been raised by epidemiological studies such as those by Wertheimer and Leeper [1979] and by Savitz et al [1988]. The studies showed an association between the incidence of childhood leukemia and

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residence in proximity to electricity distribution wiring. The homes of cases and controls were ranked according to a wiring configuration based on the number and thickness of wires in the local distribution network. The classification originally divided homes into two groups described as low or high current configurations. In a further paper studying the incidence of adult cancers [Wertheimer and Leeper, 1982], the wiring configuration was expanded to four groups described as very low, ordinary low, ordinary high and very high current configurations (VLCC, OLCC, OHCC and VHCC). However when Savitz et al used spot measurements of magnetic field instead of the wiring configuration, the association of magnetic fields with childhood leukemia became weaker.

The above work raised questions about the validity of the wiring configuration or spot measurements as estimates of magnetic field exposure. Kaune et al [1987] measured magnetic fields in 43 houses for 24-hour periods and found a weak correlation between the time-average field and the expanded Wertheimer-Leeper wiring configuration (correlation coefficient 0.41). There was a slightly greater correlation between the average field and spot measurements (correlation coefficient = 0.50). A further improvement was achieved when the time-average measurements were correlated with a revised wiring configuration (correlation coefficient = 0.72). Similarly, Barnes et al [1988] found a weak correlation between the wiring configuration and spot measurements of magnetic fields although the variation within wiring configuration groups was large. These studies demonstrate the need for a more accurate method of exposure assessment.

The purpose of this paper is to present a simple model which permits calculation of the magnetic field at all points in a house from only a few measurements. The model was tested in 24 houses with a comparison of observed and predicted fields over a 24-hour period in each house. One house was investigated in greater detail with a comparison of observed and predicted fields in each room. In addition, data were collected for one week in this house to determine the time period over which measurements should be made to avoid temporal variability in the results. Finally, the model is applied to a theoretical study of field variations in this house.

THE MODEL

The sources which can contribute to 60 Hz magnetic fields within a home are classified as: 1) transmission facilities, 2) distribution facilities, 3) house wiring and 4) appliances. The contribution of each source to the total magnetic field depends on the electric current in the conductors, the phase of the current, the distance of the conductor from the point of measurement and the geometry of the conductor circuits. This makes the accurate calculation of the total magnetic field in a residence an extremely complex task. However, the problem can be simplified if some reasonable assumptions are made.

i) Transmission and Distribution Lines

The contribution from sources external to the house (subsequently referred to as the ambient magnetic field) is assumed to be spatially uniform within the house. It is also assumed that the ambient magnetic field has a vertical component only. These assumptions are valid under two conditions. Firstly, the distance of the house to

transmission and distribution lines is large compared to the size of the house and secondly, the main contribution to the field results from net current on the lines. By simplifying the problem in this way, the ambient magnetic field can be measured with a single one-axis coil at one location in the house. However, the location of the probe must be carefully chosen to avoid the influence of other residential magnetic field sources such as grounding current and appliances. These sources are discussed below.

ii) House Wiring (Grounding Current)

Most house wiring does not produce significant magnetic fields because the wires leading to appliances carry equal and opposite currents. The magnetic fields set up by these currents cancel if the conductors are close together as is usually the case. However, the common North American practice of grounding the neutral wire of the service drop to a metal water pipe can produce a net current on the service drop, grounding wire and plumbing as illustrated in Figure 1. This figure shows the ac voltage signs and the current directions at a particular instant in time.

Net current occurs because appliance loads (indicated by R1 and R2 in Figure 1) on the positive (+120 V) and negative (-120 V) voltage wires will not normally be balanced. The unbalanced current, which is the difference between the currents on the positive and negative lines (1 A in the example shown in Figure 1), must find its way back to the distribution transformer by other routes. Two possibilities are shown in Figure 1. A fraction of the current flows back up the neutral wire while the remainder flows along the ground wire to the metal water pipe, along the water main and up a neighbour's (house 2) neutral wire. In this example, 0.3 A flows down the ground wire in house 1 while 0.7 A flows back up the neutral wire. Consequently, there is a net current flowing in the service drop and through the grounding circuit of 0.3 A. It should be noted that Figure 1 represents a simplified case where the power in house 2 is switched off. If the power were on in house 2, it would contribute to the ground wire/neutral wire current in house 1. The situation becomes extremely complex when many houses served from the same distribution transformer are also connected by a metal water service. In this case the net current on the ground wire and service drop in one house depends on the power usage in all the other houses.

The ground wire/service drop net current (subsequently referred to as grounding current) can be an important source of residential magnetic fields and is central to the model presented here. Unlike the field from external sources, the magnetic field generated by the grounding current will vary significantly through the house as a function of distance from the grounding circuit conductors. The grounding current magnetic field is calculated by first plotting the geometry of the grounding circuit conductors as shown schematically in Figure 2. The circuit includes the service drop, the ground wire and the water pipe. The field due to 1 A flowing through this circuit is calculated and then multiplied by the current measured on the circuit. The magnetic field due to the grounding current is then added to the ambient field (due to external sources) to give the total field in the house at any position or time.

iii) Appliances

The inclusion of appliances in the model complicates the calculation of residential magnetic fields. Gauger [1985] has shown that the magnetic fields due to appliances fall off rapidly with distance. Therefore, it was decided that the model should be formulated without appliance contributions to keep the measurements as simple as possible.

CALCULATION OF MAGNETIC FIELDS

The ac magnetic field at a point (**r**) in space and at time (t) is represented mathematically by a vector $\mathbf{B}(\mathbf{r},t)$. According to the model, the total magnetic field is given by

$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}_a(\mathbf{r},t) + \mathbf{B}_g(\mathbf{r},t) \tag{1}$$

where $\mathbf{B}_a(\mathbf{r},t)$ is the ambient field and $\mathbf{B}_g(\mathbf{r},t)$ is the field due to the grounding current. The ambient field is modeled as spatially uniform and vertical. Therefore, it can be written in the form

$$\mathbf{B}_a(\mathbf{r},t) = (0,0,B_{az}(t)) \tag{2}$$

where

$$B_{az}(t) = B_a(t)\cos(\omega t + \delta_a). \tag{3}$$

Here, ω is $2\pi f$ where f is 60 Hz and δ_a is the phase of the ambient field relative to the phase of a reference voltage. The amplitude of the ambient field, $B_a(t)$, varies with time as loads in the system change. The grounding current magnetic field is given by

$$\mathbf{B}_g(\mathbf{r},t) = \mathbf{U}_g(\mathbf{r})\, I_g(t) \tag{4}$$

where $\mathbf{U}_g(\mathbf{r})$ is the magnetic field at a point calculated for 1 A flowing in the grounding circuit and $I_g(t)$ is the actual current flowing in the grounding circuit. Like the ambient field, the grounding current is also represented as a 60 Hz phasor,

$$I_g(t) = I_g(t)\cos(\omega t + \delta_g). \tag{5}$$

The total field is given by

$$\mathbf{B}(\mathbf{r},t) = (B_{gx}(\mathbf{r},t)\ ,\ B_{gy}(\mathbf{r},t)\ ,\ [B_{gz}(\mathbf{r},t) + B_{az}(t)]), \tag{6}$$

and the root-mean-square (rms) magnetic field $\underline{B}(\mathbf{r},t)$ is given by

$$\underline{B}(\mathbf{r},t) = (\underline{B}^2_x(\mathbf{r},t) + \underline{B}^2_y(\mathbf{r},t) + \underline{B}^2_z(\mathbf{r},t))^{1/2} \tag{7}$$

where $\underline{B}_x$, $\underline{B}_y$ and $\underline{B}_z$ are the rms components of the field. Then the square of the rms total field is

$$\underline{B}^2(r,t) = [U_{gx}^2(r) + U_{gy}^2(r) + U_{gz}^2(r)]\underline{I}_g^2(t) + \underline{B}_{az}^2(t) \qquad (8)$$

$$+ 2\underline{B}_{az}(t)U_{gz}(r)\underline{I}_g(t)\cos(\delta_a - \delta_g).$$

where underlining indicates an rms quantity.

Equation (8) shows that the total magnetic field in the house can be calculated from three measurements:

a) The location of the ground circuit conductors (electricity service drop, grounding wire and water service pipe).

b) The net current on the grounding circuit.

c) The ambient magnetic field measured at one position and its phase relative to the grounding current.

INSTRUMENTATION

A data acquisition system (DAS), shown schematically in Figure 3, was designed and built by Donnelly [1989] to record the magnitude and phase of the current on the water service pipe and the ambient magnetic field. The same system was used to record the magnitude and phase of the magnetic field at the location of a test probe so that model predictions could be compared with direct measurements.

The DAS consisted of a portable computer (Sharp model PC-7220) containing an analog to digital conversion board (Data Translation 2825, Marlboro, Ma.) and a custom built signal conditioning unit which converts all input channels to calibrated voltages. The first input channel is a voltage reference taken from the 120 V power supply and is used to obtain the relative phases of the other input channels. A second channel records the ground current reading from a 1000:1 clamp-on current transformer. Four magnetic field inputs record the measurement of the ambient field (the vertical component only, sensed by the auxiliary coil) and the three components of the magnetic field at the 3-axis probe. The channels are polled sequentially for two 60 Hz cycles to obtain 32 samples on each channel. The waveforms are processed by a fast Fourier transform algorithm to obtain the magnitude and phases of the Fourier components up to 420 Hz. Only the 60 Hz component is analyzed in this work.

A portable magnetic field meter (Model 42A-1, Monitor Ind., Boulder, Co.) was used to detect the location of ground circuit conductors. The grounding circuit geometry was mapped out and the magnetic field ($\mathbf{U}_g$) due to a current of 1 A flowing in the circuit was calculated using a computer programme (MAG-PC, Infolytica Corp., Montreal).

RESULTS

i) Model Tested in 24 Houses

An experimental test of the model was performed in 24 houses in the Metropolitan Toronto area. Houses were selected non-randomly to obtain a variety of cases: old and new construction, overhead and underground distribution, and transmission lines close and distant. The magnetic field was recorded at one location in each house for a time period of either 16 or 24 hours. The fields were averaged over the measurement time period and compared to the field predicted by the model averaged over the same time period. The results, shown in Table 1 are presented graphically in Figure 4. Agreement to better than 1.5 mG was found in 75% of the cases.

The relatively large lack of agreement observed in houses D, M, and Q can be attributed to the existence of multiple grounding current paths considered further in the DISCUSSION section below. House N, with a 6.5 mG disagreement, was very close to a transmission line and the ambient field measured in the vicinity of the house with the portable field meter was seen to vary by a factor of four from one side of the house to the other. However, the model gave good predictions in two other houses (F and O) which were close to transmission lines. In the case of house T, where the test probe had been placed close to the ground circuit in a field of 30.83 mG, the lack of agreement can be attributed to uncertainty in the measurement of the location of the test probe relative to the grounding circuit conductors.

ii) Detailed Test in One House

Spot-in-time magnetic field readings were taken in nine rooms in house A and compared in Figure 5 to the model predictions for the same point in time at those locations. The measured fields varied between 0.8 mG and 7.0 mG and agreed reasonably well with model predictions. The mean values of the observed and predicted fields were 2.75 mG and 2.44 mG, respectively, while the rms difference between them was 1.1 mG.

iii) Week-Long Data Collection

The grounding current, ambient magnetic field and total magnetic field were measured in house A for a seven-day period, with the hourly averages shown in Figure 6. Variations of up to 400% are observed in the hourly averages, due primarily to large fluctuations in the grounding current. It is interesting to note that the ambient field is quite constant as compared to the transient nature of the grounding current in this house. Also, the total field shows the same temporal variation as the grounding current. The hourly averages have a mean of 4.4 mG and a standard deviation of 1.2 mG. In contrast, the daily averages shown in Figure 7 have a standard deviation of 0.4 mG, or 9% of the mean.

iv) **Application of the Model**

The model was used to simulate a large data gathering exercise in house A. The magnetic field was calculated at 484 points in the house located at 1 metre intervals throughout the volume of the house. For this exercise the week-long averages of the ground current (1.88 A) and ambient field (1.3 mG) were used. Figure 8 is a histogram of magnetic field values calculated on the house grid. The mean value is 2.4 mG with an upper 5%-tile value of 6.7 mG. The average field due to the grounding current alone was 1.7 mG, 30% larger than the ambient field. Since the fields from the two sources combine as vectors as shown in equation (8), their sum (1.7 mG + 1.3 mG) is not equal to the mean of the total field (2.4 mG).

DISCUSSION

This work was aimed at developing and testing a method for determining residential magnetic field levels from a few simple measurements. A test of the model in 24 houses showed that 24-hour average predicted and measured fields agreed to within 1.5 mG in 75% of the cases. The correlation coefficient was 0.95 between the measured and calculated magnetic fields, including all 24 houses. However, this value is strongly influenced by the inclusion of the single point for house T. A more robust estimate of the correlation coefficient is 0.87 for 23 houses, excluding house T.

There are two major circumstances under which the simple model assumptions break down. In some houses grounding current can flow in several conductors. Figure 9 illustrates how the grounding of individual electrical appliances to the water service via metal pipes can provide alternate paths from the electric service entrance neutral block to the water pipe. The extra paths are not included in the model and therefore the calculation of the total magnetic field will be in error. However, in house M where 67% of the grounding current flowed through alternate paths, the model still gave reasonable predictions. In this case the calculated field was only 25% less than the measured field. The presence of alternate grounding current paths can be determined by measuring the current on the ground wire and on the water pipe. If they are not equal, other conductors must be carrying grounding current. Problems also arise if transmission and distribution lines are located very close to a house. In this case the assumption of a spatially constant and vertical ambient field from external sources is invalidated. Once again though, the effect of this error on temporal and spatial average fields may be small.

This study also investigated variations in magnetic fields both spatially and temporally. This information may be important if a method similar to the one presented is used to assess exposure. The detailed test in one house showed a factor of ten variation in field values depending on location within the house. The variability depends on the particular grounding circuit geometry and the relative phase of the grounding current and the ambient magnetic field. The two fields will cancel in some locations and reinforce in others. Also close proximity to the ground wire can result in very high field strengths. The results indicate that spot-spatial magnetic field measurements can be very inaccurate as a measure of exposure. The week-long data collection suggests that spot-time measurements can be very inaccurate. The standard deviation of 24-hour

averages about the week–long mean was one–third that of the standard deviation of hourly averages. Possible seasonal variations in residential magnetic fields were not investigated. The relative contributions of grounding current and external sources to the magnetic field in the test house were calculated using the model. The two sources gave approximately equal contributions to the volume averaged magnetic field. This application demonstrates how the model can be used to form a detailed profile of magnetic field strengths throughout a house.

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Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted:

D.L. Mader
Associate Research Scientist
Science Section

D.A. Barrow[1]
Temporary Engineer
Science Section

K.E. Donnelly[2]
Physicist
Science Section

M.D. Sherar
Temporary Engineer
Science Section

R.R. Scheer
Intermediate Technician
Science Section

[1]Present location: SHL Systemhouse Inc, Toronto.

[2]Present location: Health & Safety Division, Technical Safety Standards Department, Pickering.

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TABLE 1: EXPERIMENTAL STUDY IN 24 HOUSES

House	Notes		Phase Ambient (deg)	Phase Current (deg)	Ambient Field (mG)	Ground Current (A)	Measured Field (mG)	Calculated Field (mG)
A	O	-	-126	-11	1.16	1.40	5.37	5.31
B	O	-	12	-84	0.38	1.76	2.21	2.51
C	O	I	-16	-39	0.00	0.77	1.81	3.49
D	O	M	72	-48	0.24	2.53	7.23	3.97
E	U	-	61	149	0.38	0.01	0.57	0.38
F	U	T	54	-8	1.17	0.90	1.56	1.46
G	U	-	97	-58	0.87	1.79	2.28	2.59
H	O	-	-82	11	2.48	2.48	4.40	3.02
I	O	W	131	162	0.61	0.19	0.84	0.62
J	U	-	53	7	0.69	0.78	1.48	1.01
K	U	I,C	105	-71	1.32	4.70	5.13	3.81
L	U	M	159	-45	2.08	0.73	1.68	2.08
M	O	M	-71	-46	1.02	5.20	12.20	9.09
N	U	T	-6	-64	3.74	0.34	10.39	3.86
O	U	T	127	-83	5.06	0.15	5.79	5.07
P	U	-	50	-34	0.09	0.30	0.36	0.14
Q	O	M	-15	62	2.49	0.71	0.99	2.67
R	U	-	141	-91	0.55	0.03	0.67	0.56
S	O	-	27	112	0.50	3.13	1.25	1.50
T	O	P	34	59	0.27	2.36	30.83	46.69
U	O	-	-57	30	0.26	3.34	1.63	0.29
V	U	-	32	-21	0.39	1.28	0.72	1.20
W	O	-	-133	-18	0.85	1.58	1.49	1.49
X	O	W	77	21	0.12	0.00	0.27	0.12

KEY

O Overhead distribution lines.
U Underground distribution lines.
I Inadvertent connection between the copper wire and a conductor resulting in alternate current paths.
M Multiple current paths to the water service pipe.
T High Voltage Transmission lines within 10 metres of the house.
W Well water supply.
C Common water pipe (Town house complex).
P Close proximity between 3-axis probe and grounding circuit as surveyed.

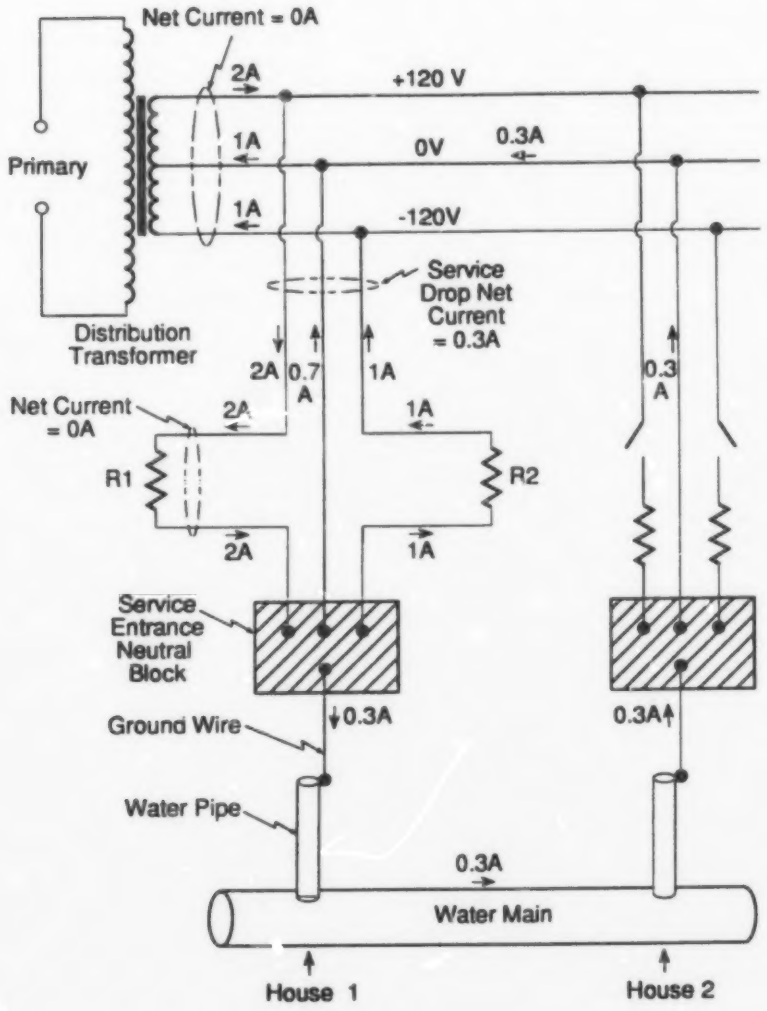

Fig. 1: Schematic diagram of the wiring of two houses connected by a metallic water service. The practice of grounding the service entrance neutral block to the water pipe results in net current on the service drop.

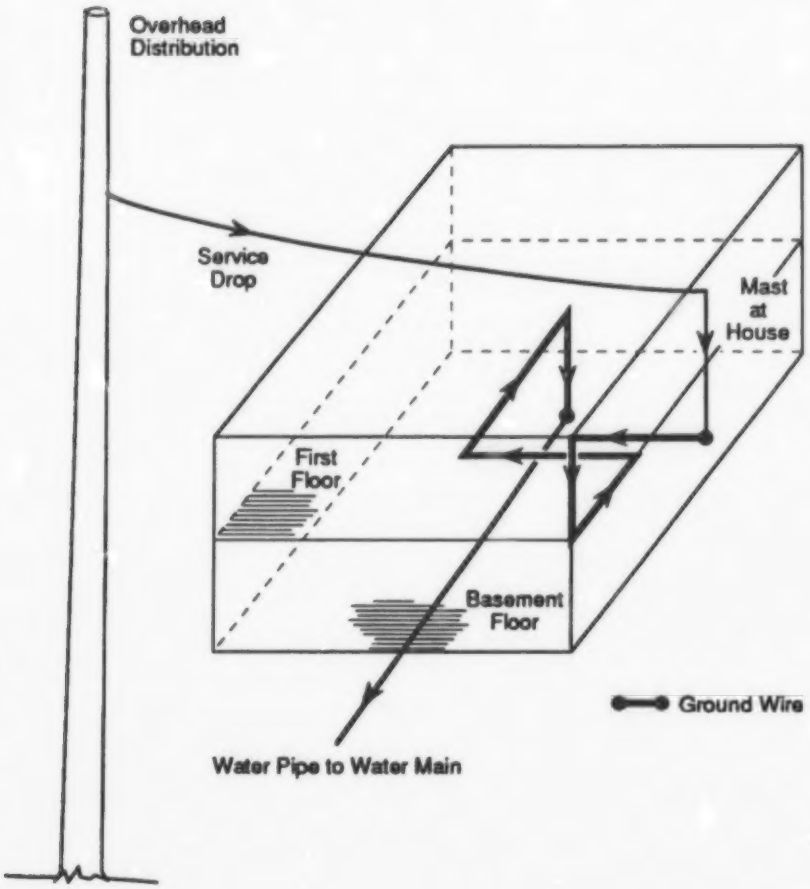

Fig. 2: Geometry of grounding circuit including electricity service drop, ground wire and water pipe.

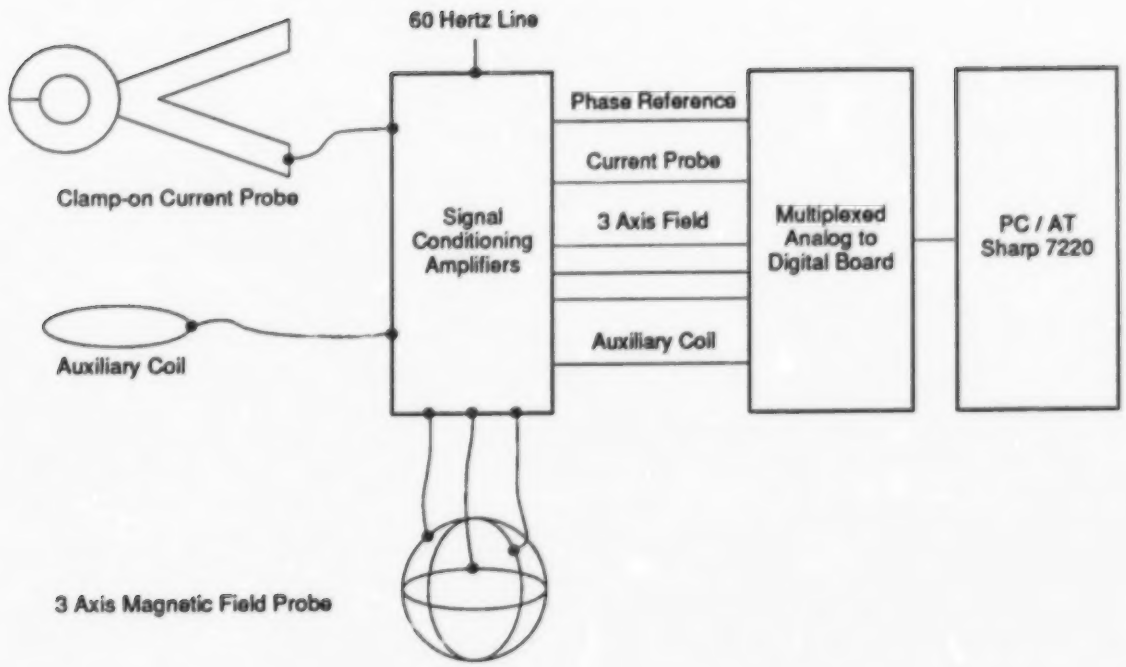

Fig. 3: Data acquisition system for measuring the amplitude and phase of grounding current, ambient field and magnetic field at test probe location.

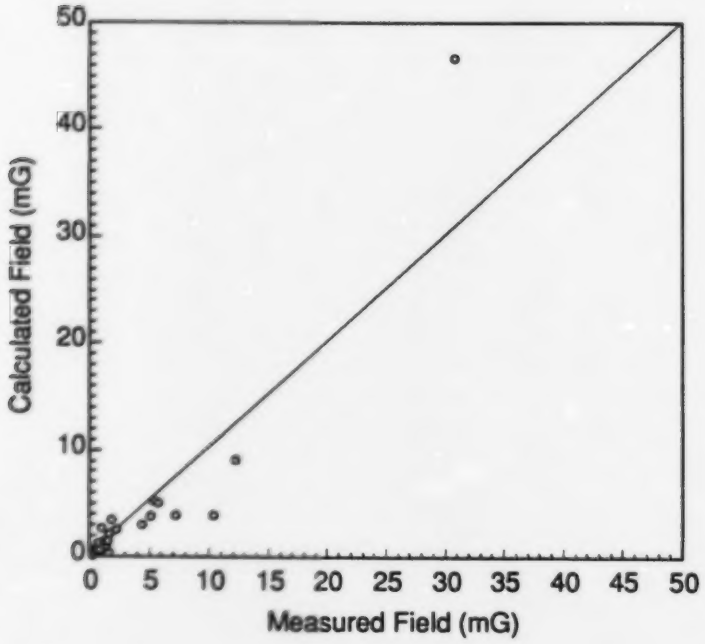

Fig. 4: Comparison of time-averaged measured and calculated magnetic fields at a single location in 24 houses.

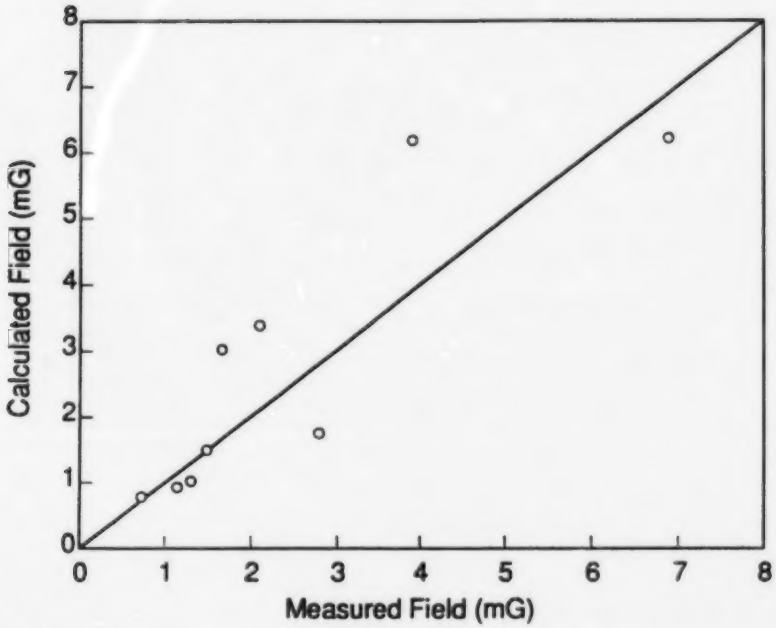

Fig. 5: Comparison of measured and calculated fields in nine rooms of test house.

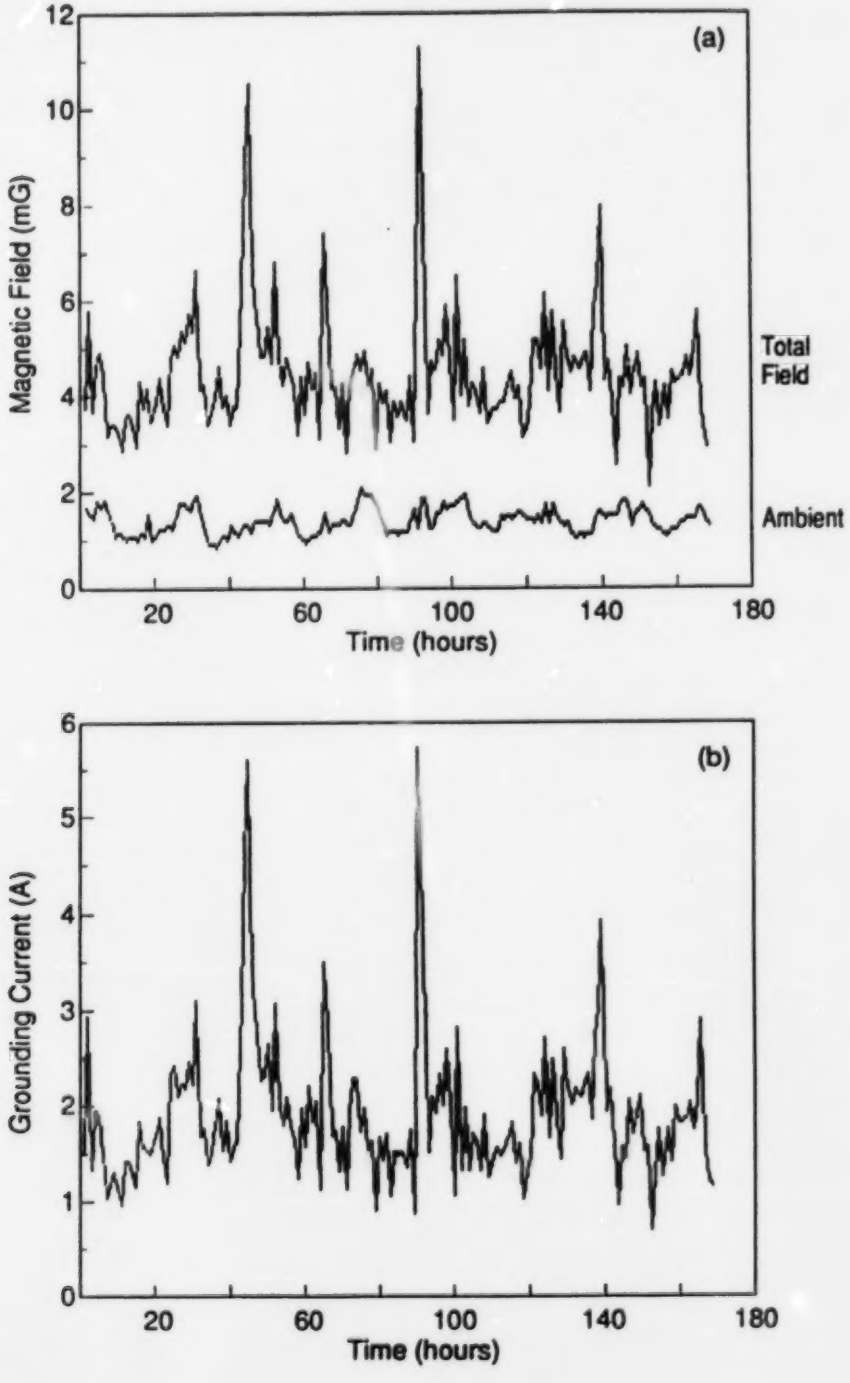

Fig. 6: Week-long data collection in test house. (a) Total magnetic field and ambient field measured as a function of time. (b) Grounding current measured on the water service pipe during the same time period as (a).

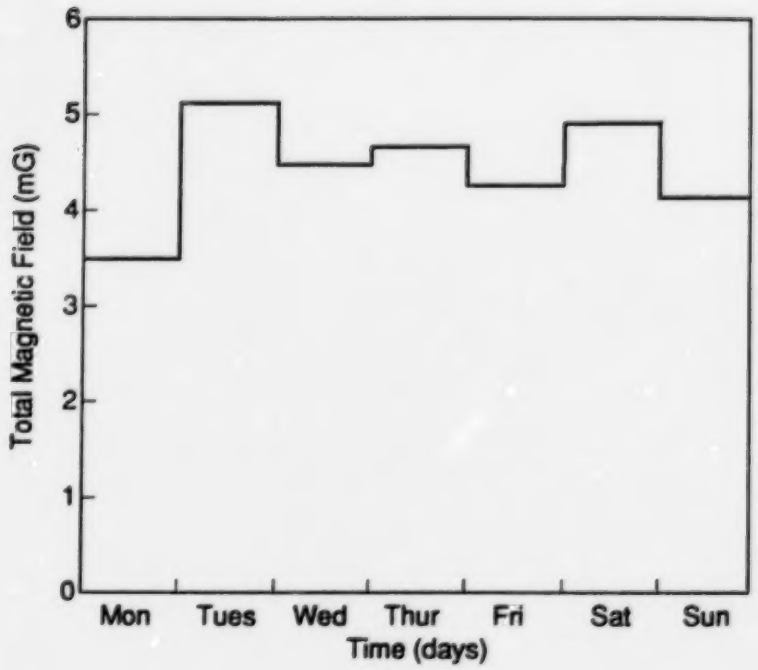

Fig. 7: Total magnetic field values from figure 6 are averaged over each 24-hour period.

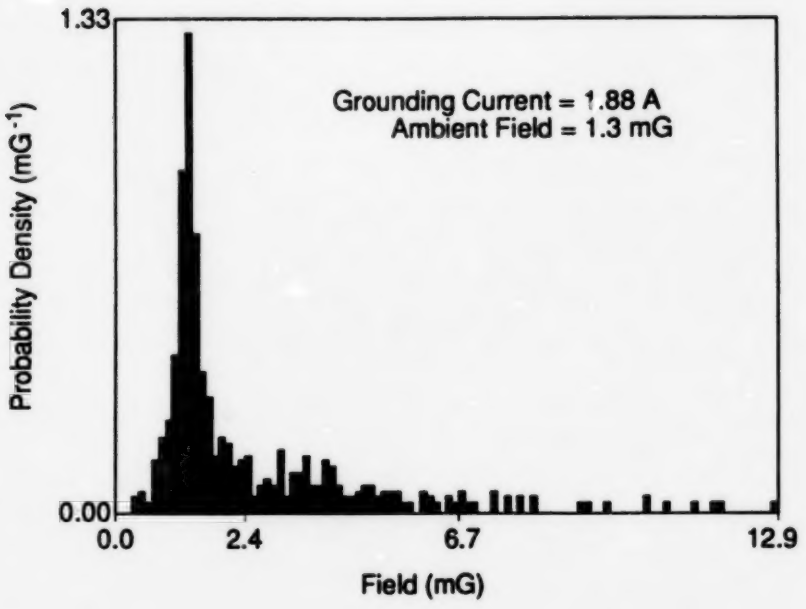

Fig. 8: Histogram of field values calculated throughout the volume of house A.

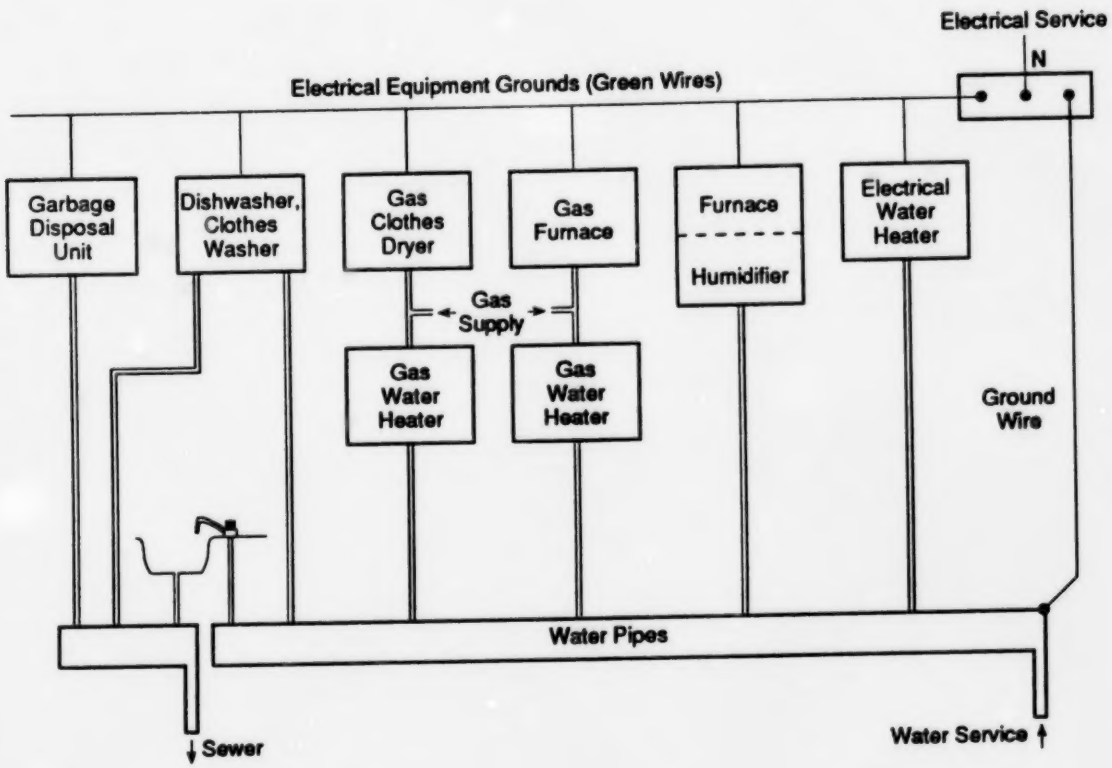

Fig. 9: Schematic diagram of alternate paths that can carry grounding current.